

Absolute electron and positron fluxes from PAMELA/Fermi and Dark Matter

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We extract the positron and electron fluxes in the energy range 10 - 100 GeV by combining the recent data from PAMELA and Fermi LAT. The *absolute positron and electron* fluxes thus obtained are found to obey the power laws: $E^{-2.65}$ and $E^{-3.06}$ respectively, which can be confirmed by the upcoming data from PAMELA. The positron flux appears to indicate an excess at energies $E \gtrsim 50$ GeV even if the uncertainty in the secondary positron flux is added to the Galactic positron background. This leaves enough motivation for considering new physics, such as annihilation or decay of dark matter, as the origin of positron excess in the cosmic rays.

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I. INTRODUCTION

Recent results from the Fermi Large Area Telescope (LAT) [1] indicate an excess of the electron plus positron flux ($\Phi_{e^-} + \Phi_{e^+}$) at energies above 100 GeV. This also confirms the earlier results from ATIC [2] and PPB-BETS [3], apart from the peak at around 600 GeV in the ATIC data. The HESS [4] collaboration also reported an excess of $\Phi_{e^-} + \Phi_{e^+}$ above 340 GeV, confirming their previous results [5]. Meanwhile PAMELA data [6] have shown an excess in $(\Phi_{e^+}/\Phi_{e^-} + \Phi_{e^+})$, compared to the Galactic background at 10-100 GeV. PAMELA also confirms the earlier results from HEAT [7] and AMS [8]. Somewhat surprisingly, PAMELA did not find any antiproton excess below 100 GeV [9].

Although standard astrophysical sources may be able to account for the anomaly [10], the positron excess at PAMELA and the electron plus positron flux of Fermi have caused a lot of excitement being interpreted as indirect detection of dark matter (DM) [11, 12]. If dark matter couples to standard model (SM) particles then the annihilation or decay of DM could, indeed, be the origin of cosmic ray anomalies observed by PAMELA and Fermi. The annihilation or decay of DM produces an equal number of particles (electrons and/or protons) and antiparticles (positrons and/or antiprotons), which could form a significant component of the observed cosmic rays. Since the background matter fluxes in the Galactic medium are at least one order of magnitude larger than the antiparticle fluxes, the DM signal is better observable in the Galactic antimatter fluxes.

Currently the antiproton flux up to 100 GeV in the PAMELA data is consistent with the Galactic background. However, there is an approximately 10% excess in the PAMELA $(\Phi_{e^+}/(\Phi_{e^-} + \Phi_{e^+}))$ data over the background. Since this excess is not given in terms of the absolute positron flux, it gives rise to various ambiguities [13]. The main source of these ambiguities is that the excess of the positron flux, as given by the PAMELA collaboration, crucially depends on the uncertainty in the background of the electron as well as the positron fluxes [14, 15, 16]. Therefore it is not apparent that PAMELA implies a statistically significant positron excess until one shows it in terms of an absolute positron flux.

In this paper we make an attempt to disentangle the abso-

lute positron flux up to an energy of 100 GeV by combining the current data from PAMELA and Fermi. We quantify the excess of the absolute positron flux after discussing the uncertainty in the secondary positron background flux [15, 16]. It is shown that the combined PAMELA and Fermi data seem to indicate an excess in the absolute positron flux for $E \gtrsim 50$ GeV. We then demonstrate the compatibility of this excess with the annihilating DM scenario, and we compare this scenario with the current Fermi data. Moreover, we find that the absolute positron and electron fluxes admit power law spectra of $E^{-2.65}$ and $E^{-3.06}$ respectively.

II. ABSOLUTE POSITRON FLUX AND BACKGROUND

So far no experiment has provided the absolute magnitude of the Galactic positron flux. Below 100 GeV the excess in the PAMELA data is about 10%. On the other hand, the electron plus positron flux at Fermi does not seem to indicate any excess below 100 GeV. In order to accept the positron excess interpretation of PAMELA, it is crucial to show an excess in the absolute magnitude of the positron flux itself.

To decisively settle this issue, we combine the data from PAMELA and Fermi and extract the absolute positron and electron fluxes as:

$$\begin{aligned}\Phi_{e^+} &= \left(\frac{\Phi_{e^+}}{\Phi_{e^-} + \Phi_{e^+}} \right)_{\text{PAMELA}} \times (\Phi_{e^-} + \Phi_{e^+})_{\text{Fermi}}, \\ \Phi_{e^-} &= (\Phi_{e^-} + \Phi_{e^+})_{\text{Fermi}} - \Phi_{e^+}.\end{aligned}\quad (1)$$

In order to utilize Eq. (1), we need $\Phi_{e^-+e^+}$ from Fermi and $\Phi_{e^+}/(\Phi_{e^-} + \Phi_{e^+})$ by PAMELA in the same energy bin, so that the combined central values and uncertainties can be evaluated at a given energy E . To this end for each energy bin of the Fermi data we interpolate the PAMELA data. We evaluate the uncertainty of the absolute positron and electron fluxes as:

$$\begin{aligned}(\delta\Phi_{e^+})^2 &= (\Phi_{e^+})^2 \left(\left(\frac{\delta(\Phi_{e^+}/(\Phi_{e^-} + \Phi_{e^+}))}{\Phi_{e^+}/(\Phi_{e^-} + \Phi_{e^+})} \right)^2 + \right. \\ &\quad \left. \left(\frac{\delta(\Phi_{e^-} + \Phi_{e^+})}{\Phi_{e^-} + \Phi_{e^+}} \right)^2 \right), \\ (\delta\Phi_{e^-})^2 &= (\delta\Phi_{e^-+e^+})^2 + (\delta\Phi_{e^+})^2.\end{aligned}\quad (2)$$

Whether there is an excess or not in these combined fluxes will depend on the background expectations. The Galactic positron background fluxes were recently examined in Ref.s [14, 15, 16]. The majority of positrons in our galaxy are produced from scatterings of cosmic-ray protons with the interstellar medium. The positrons thus produced from proton-proton collisions provide background for the positrons produced from the annihilation or decay of DM. Therefore the background positrons in the Galactic medium are always secondary and can be parameterized as [17]:

$$\Phi_{\text{sec}, e^+}^{\text{bkg}} = \frac{4.5\epsilon^{0.7}}{1 + 650\epsilon^{2.3} + 1500\epsilon^{4.2}} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \quad (3)$$

where the dimensionless parameter is $\epsilon = E/(1 \text{ GeV})$. However, there is a large uncertainty in the secondary positron fluxes coming from cosmic ray propagation [13], as shown in FIG. 1. In the Galactic medium the flux of the primary and secondary electrons is about an order of magnitude larger than that of the positrons. These electron fluxes are parameterized as [17]:

$$\begin{aligned} \Phi_{\text{prim}, e^-}^{\text{bkg}} &= \frac{0.16\epsilon^{-1.1}}{1 + 11\epsilon^{0.9} + 3.2\epsilon^{2.15}} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \\ \Phi_{\text{sec}, e^-}^{\text{bkg}} &= \frac{0.70\epsilon^{0.7}}{1 + 11\epsilon^{1.5} + 600\epsilon^{2.9} + 580\epsilon^{4.2}} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}. \end{aligned} \quad (4)$$

In FIG. 1 we have shown the absolute positron and electron fluxes: Φ_{e^+} and Φ_{e^-} , extracted from PAMELA and Fermi, up to 100 GeV. The corresponding error bars are also shown. From FIG. 1 it can be seen that the extracted positron flux exhibits a clear excess with respect to the background for $E \gtrsim 50 \text{ GeV}$. There is a minor excess of electron plus positron fluxes if we assume a 10% reduced background:

$$\Phi_{e^-+e^+}^{\text{rbkg}} = 0.0253\epsilon^{-3.206} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}. \quad (5)$$

The reduced background can be thought of as uncertainty in the current estimation of electron flux [14]. Here we compare this reduced background with the $e^- + e^+$ spectrum of Fermi.

III. POSITRON EXCESSES FROM DM ANNIHILATION

Annihilation of DM produces equally positrons and electrons in the Galactic medium which can be a significant component of cosmic rays. However, as we discussed, the background electron flux in the Galactic medium is much larger than the background positron flux. Therefore finding a DM signal, if any, in the Galactic positron flux is easier than finding one in the electron flux. Thus, in what follows, we will focus on the positron flux in the cosmic rays.

Recent studies have shown that the $e^- + e^+$ spectrum of Fermi and the excess at PAMELA, without an excess in antiprotons, can simultaneously be explained with TeV scale

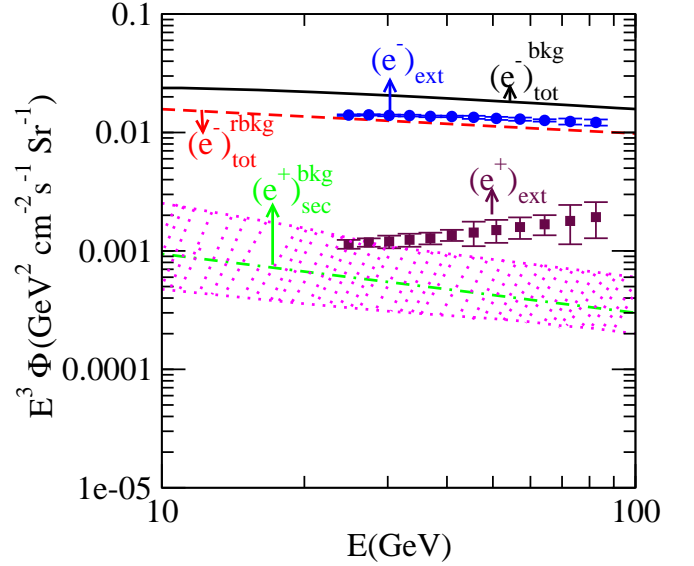


FIG. 1: The total (primary plus secondary) background electron flux (black-solid line), the total reduced background electron flux (red-dashed line) and the positron background (green dot-dashed line) with propagation uncertainty (pink band) are shown in the energy range 10-100 GeV. Electron (blue-circle) and positron (maroon-square) fluxes, extracted from PAMELA and Fermi, are also shown with respect to their backgrounds. The power law fitting of positron and electron fluxes are found to be $E^{-2.56}$ and $E^{-3.06}$ respectively.

DM, which annihilates to $\mu^+\mu^-$ and $\tau^+\tau^-$ [18, 19]. This explanation requires either the local density of DM or its annihilation cross section to be considerably higher than typically expected. This enhancement is referred to as the “boost factor”. The origin of such a boost factor could be astrophysical: large inhomogeneities, caused by merging substructures for example, could enhance the local density. Alternatively, assuming a homogeneous distribution of dark matter in the galaxy, its annihilation cross section to $\mu^+\mu^-$ and $\tau^+\tau^-$ pairs at present could be significantly larger than that of the typical thermal relic, which is a few times $10^{-26} \text{ cm}^3/\text{s}$ [20]. The boost might arise from a combination of astro- and particle physics effects. Several possible explanations for the boost factor have been proposed, in particular Sommerfeld enhancement of the dark matter annihilation cross-section [20, 25, 26, 27, 28, 29], non-thermal dark matter from thermal relic decay [30, 31, 32, 33, 34, 35, 36, 37, 38], annihilation of thermal relic by resonance [39, 40] and so on. If the boost factor originates from particle physics then its value is model dependent, but it should be constrained by the Big-Bang Nucleosynthesis (BBN) [21], gamma ray and radio observations [22], diffuse gamma ray background [23] and more severe constraints from gamma rays produced by inverse Compton scattering of the energetic electrons and positrons from DM annihilations [24].

A. Positron Propagation

If the positrons are produced via the annihilation or decay of DM, then they travel in the galaxy under the influence of a magnetic field which is assumed to be order of a few micro-gauss. As a result the motion of positrons can be thought of as a random walk. The positron flux in the vicinity of the solar system can be obtained by solving the diffusion equation [15, 41, 42]

$$\frac{\partial}{\partial t} f_{e^+}(E, \vec{r}, t) = K_{e^+}(E) \nabla^2 f_{e^+}(E, \vec{r}, t) + \frac{\partial}{\partial t} [b(E) f_{e^+}(E, \vec{r}, t)] + Q(E, \vec{r}), \quad (6)$$

where $f_{e^+}(E, \vec{r})$ is the number density of positrons per unit energy, E is the energy of the positron, $K_{e^+}(E)$ is the diffusion constant, $b(E)$ is the energy-loss rate and $Q(E, \vec{r})$ is the positron source term. The positron source term $Q(E, \vec{r})$ due to DM annihilation is given by:

$$Q(E, \vec{r}) = \frac{1}{2} n_{\text{DM}}^2(\vec{r}) f_{\text{inj}}^{e^+}, \quad (7)$$

where the factor $1/2$ accounts the Majorana nature of DM, and the injection spectrum can be given as

$$f_{\text{inj}}^{e^+} = \langle \sigma_{\text{DM}} | v_{\text{rel}} \rangle \frac{dN_{e^+}}{dE}. \quad (8)$$

In the above equation the fragmentation function dN_{e^+}/dE represents the number of positrons with energy E which are produced from the annihilation of DM. We assume that the positrons are in steady state, i.e. $\partial f_{e^+}/\partial t = 0$. Then from Eq. (6), the positron flux in the vicinity of the solar system can be obtained in a semi-analytical form [15, 41, 42]

$$\Phi_{e^+}(E, \vec{r}_\odot) = \frac{v_{e^+}}{4\pi b(E)} (n_{\text{DM}})_\odot^2 \langle \sigma_{\text{DM}} | v_{\text{rel}} \rangle \times \int_E^{M_{\text{DM}}} dE' \frac{dN_{e^+}}{dE'} I(\lambda_D(E, E')), \quad (9)$$

where $\lambda_D(E, E')$ is the diffusion length from energy E' to energy E and $I(\lambda_D(E, E'))$ is the halo function which is independent of particle physics. An analogous solution for the electron flux can also be obtained.

The net positron flux in the galactic medium then can be given by

$$(\Phi_{e^+})_{\text{Gal}} = (\Phi_{e^+})_{\text{bkg}} + \Phi_{e^+}(E, \vec{r}_\odot). \quad (10)$$

The first term in the above equation is given by Eq. (3) while the second term is given by Eq. (9), which depends on various factors: $b(E)$, $\lambda_D(E, E')$, $I(\lambda_D(E, E'))$, v_{e^+} , $(n_{\text{DM}})_\odot$ and the injection spectrum $f_{\text{inj}}^{e^+}$. The energy loss due to inverse Compton scattering and synchrotron radiation with galactic magnetic field, described by $b(E)$, is determined by the photon density and the magnetic field strength. Its value is taken to be $b(E) = 10^{-16} \text{e}^2 \text{GeV s}^{-1}$ [17]. The number density of DM in the solar system is given by

$$(n_{\text{DM}})_\odot = \frac{\rho_\odot}{M_{\text{DM}}}, \quad (11)$$

where $\rho_\odot \approx 0.3 \text{ GeV/cm}^3$. In the energy range we are interested in, the value of v_{e^+} is taken approximately to be c , the velocity of light. The values of diffusion length $\lambda_D(E, E')$ and the corresponding halo function $I(\lambda_D(E, E'))$ are based on astrophysical assumptions [15, 41, 42]. By considering different heights of the galactic plane and different DM halo profiles the results may vary slightly. In the following for the height of galactic plane we take $\lesssim 4 \text{ kpc}$, which is referred to as "med" model [15, 42], and we have used the NFW DM halo profile [43]

$$\rho(r) = \rho_\odot \left(\frac{r_\odot}{r} \right) \left(\frac{1 + \left(\frac{r_\odot}{r_s} \right)}{1 + \left(\frac{r}{r_s} \right)} \right)^2, \quad (12)$$

to determine the halo function $I(\lambda_D(E, E'))$, where $r_s \approx 20 \text{ kpc}$ and $r_\odot \approx 8.5 \text{ kpc}$. In FIG.s (2) and (4) we have shown the

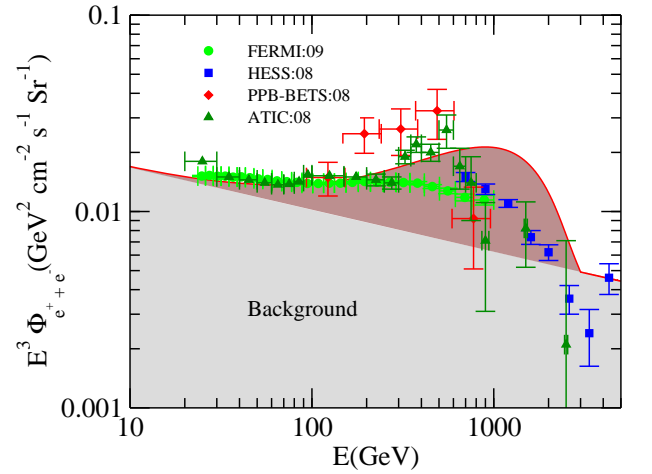


FIG. 2: $e^- + e^+$ flux from annihilation of DM to $\mu^+ \mu^-$. We have used a boost factor of 5.3×10^3 , a DM mass $M_{\text{DM}} = 3 \text{ TeV}$, and the reduced background (5).

the total electron and positron fluxes from the annihilation of DM to muon and tau pairs respectively, plotted using DARK-SUSY [44]. Meanwhile, in FIG.s (3) and (5) we have shown the extracted positron flux. In the following we discuss a specific particle physics model where the DM annihilation to SM leptons can be enhanced through the Sommerfeld correction.

B. A model for Sommerfeld enhanced DM annihilation cross-section

As an illustrative example, we consider the model for Sommerfeld enhanced annihilation to muons which was proposed in Ref. [37, 47]. The SM is extended by adding a hidden sector composed of three scalars $S(1, 0, 3/2)$, $\chi(1, 0, 1)$ and $\phi(1, 0, 1)$, where the numbers inside the parenthesis are quantum numbers under gauge group $SU(2)_L \times U(1)_Y \times U(1)_{\text{hidden}}$. The SM fields are neutral under $U(1)_{\text{hidden}}$. The $U(1)_{\text{hidden}}$ will be broken at around the electroweak scale to a surviving Z_2 symmetry under which S is odd while rest of the fields, including

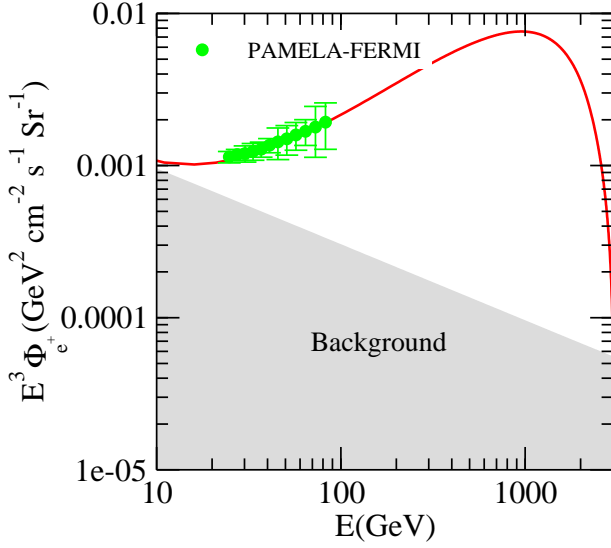


FIG. 3: Positron flux extracted from Fermi and PAMELA compared to the annihilation of DM to $\mu^+\mu^-$. The required boost factor is 5.3×10^3 for a DM mass $M_{\text{DM}} = 3$ TeV.

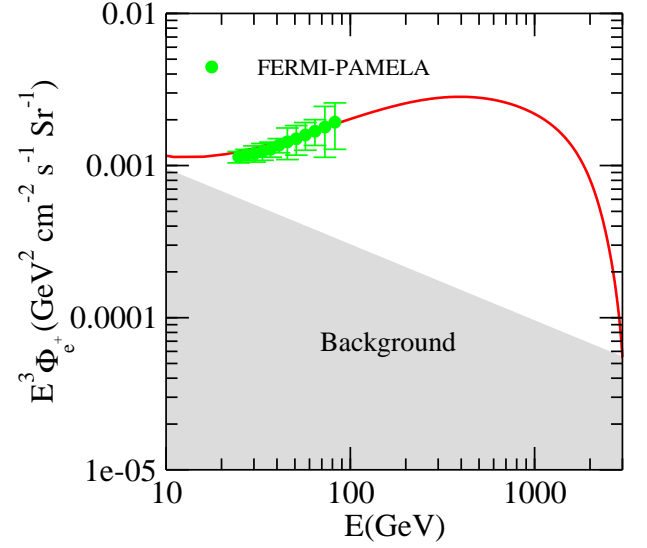


FIG. 5: Positron flux extracted from Fermi and PAMELA compared to the annihilation of DM to $\tau^+\tau^-$. The required boost factor is 5.3×10^3 for a DM mass $M_{\text{DM}} = 3$ TeV.

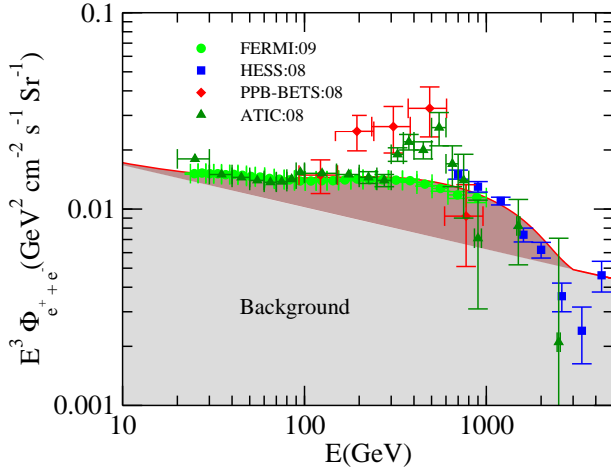


FIG. 4: $e^- + e^+$ flux from DM annihilation to $\tau^+\tau^-$. The boost factor is 6.7×10^3 and the DM mass (M_{DM}) is 3 TeV. We have used the reduced background (5).

the SM fields, are even. As a result S can be a candidate for a DM [45]. Several models have been considered in the literature [46]. Here we assume the mass of S to be a few TeV, while the masses of χ and ϕ to be of $\mathcal{O}(100)$ GeV and $\mathcal{O}(100)$ MeV respectively. The hidden sector is allowed to interact with the SM via the Higgs portal with universal renormalisable couplings. The relevant Lagrangian is then given by

$$\begin{aligned} \mathcal{L} \supseteq & f_{\text{portal}} H^\dagger H \left(S^\dagger S + \phi^\dagger \phi + \chi^\dagger \chi + \phi^\dagger \chi \right) \\ & + f_{S\phi} S^\dagger S \phi^\dagger \phi + f_{S\chi} S^\dagger S \chi^\dagger \chi + f_{S\chi\phi} S^\dagger S \chi^\dagger \phi + h.c. \end{aligned} \quad (13)$$

Below 100 GeV χ acquires a vacuum expectation value (vev) and breaks $U(1)_{\text{hidden}}$ to a surviving Z_2 symmetry under which

S is odd. It also gives a mixing between H and ϕ through the interaction term $H^\dagger H \phi^\dagger \chi$. As a result ϕ can potentially annihilate to muon pairs. Since ϕ gets a mass through the vev of H , the $\mathcal{O}(100)$ MeV scale mass of ϕ demands the universal coupling of Higgs to hidden sector to be of $\mathcal{O}(10^{-6})$. However, we have to make sure that with this coupling S should be in thermal equilibrium above its mass scale. This implies that

$$f_{\text{portal}} \gtrsim 8.36 \times 10^{-7} \left(\frac{M_S}{1 \text{ TeV}} \right)^{1/2}. \quad (14)$$

First S will freeze-out at a temperature $T_S \sim M_S/20$. However, the corresponding annihilation cross-section is known to be $\mathcal{O}(10^{-26}) \text{ cm}^3/\text{sec}$. The current annihilation of S can be enhanced through the interaction: $S^\dagger S \chi^\dagger \phi$. This interaction can generate an attractive force between S particles through the exchange of ϕ . The enhanced Sommerfeld annihilation cross-section then requires $M_\phi \lesssim \alpha M_S$ [48], where $\alpha = \lambda^2/4\pi$, the effective coupling $\lambda f_{S\chi\phi} \langle \chi \rangle / M_S$. This gives the constraint on the coupling constant to be:

$$f_{S\chi\phi} \gtrsim 0.5 \left(\frac{M_\phi}{200 \text{ MeV}} \right)^{1/2} \left(\frac{M_S}{1 \text{ TeV}} \right)^{1/2} \left(\frac{100 \text{ GeV}}{\langle \chi \rangle} \right). \quad (15)$$

Thus we see that for $f_{S\chi\phi} \gtrsim 0.5$ we can get an enhanced annihilation cross-section to explain the current anomalies at PAMELA and Fermi through S annihilation to muons. The coupling $f_{\text{portal}} \ll f_{S\chi\phi}$ ensures that antiproton fluxes from $S^\dagger S$ annihilation are suppressed.

IV. CONCLUSIONS

In this paper we disentangled the absolute electron and positron fluxes by combining the current data from PAMELA

and Fermi. The electron and positron spectra are found to follow the power laws: $E^{-3.06}$ and $E^{-2.65}$ respectively. We showed that there is a clean excess of positron flux above 50 GeV even if the propagation uncertainty of positron is added to the background. This implies that we still have enough motivation for considering DM annihilation for the explanation of current cosmic ray anomalies at PAMELA and Fermi. We then considered a variant of the model of Ref. [37] based on universal Higgs coupling to the hidden sector which can give rise to muon pairs from the annihilation of the dark matter particles.

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